

The Orbits of Meteorites from Natural Thermoluminescence

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The natural thermoluminescence (TL) of meteorites reflects their irradiation and thermal histories. Virtually all ordinary chondrites have been irradiated long enough to have reached saturation natural TL levels, and thus natural TL levels in these meteorites are determined largely by thermal history. The primary heat source for most meteorites is the Sun, and thus natural TL levels are determined primarily by the closest approach to the Sun, i.e., perihelion. By converting natural TL levels to perihelia, using an assumed albedo typical of meteoroid bodies, it is found that most ordinary chondrites had perihelia of 0.85 to 1.0 AU prior to reaching Earth. This range is similar to that calculated from meteor and fireball observations. All common classes of ordinary chondrites exhibit similar perihelia distributions; however, H and LL chondrites that fell in the local morning differ in their natural TL distribution from those that fell in the local afternoon and evening. This is consistent with earlier suggestions that time of fall reflects orbital distribution. The data also suggest that the orbits of some of the H chondrites cluster and may have come from a debris "stream" of meteoroids. If meteorites can exist in "orbital groups," significant changes in the types and number of meteorites reaching Earth could occur on the $<10^5$ -year time scale. © 1997 Academic Press

The possible existence of meteoroid streams, even as relatively minor contributors to the terrestrial flux of extraterrestrial material, is important in understanding the orbital evolution of meteoroid bodies, the rarity of potential asteroidal sources for ordinary chondrites, which account for more than 60% of meteorite falls (Greenberg and Nolan 1989), and apparent differences between meteorites currently falling and those that fell over the last few hundred thousand years and have been stored in the ice sheet of Antarctica (Koeberl and Cassidy 1991, Benoit and Sears 1993a, Wolf and Lipschutz 1995).

Precise orbits are known for only 4 meteorites (Wetherill and Chapman 1988, Brown *et al.* 1994). Orbital parameters have been estimated for another 40 meteorites from eyewitness accounts of their fall (Simonenko 1975, Wetherill and Chapman 1988), but these are of low accuracy. Limited orbital information can also be obtained from the local time of fall (Wetherill 1968). Meteorites with perihelia ~ 1 astronomical unit (AU) should usually strike the trailing side of the Earth, or the local PM, while meteorites with perihelia <1 AU should be more evenly spread over the leading and trailing sides. The large abundance of ordinary chondrites falling in the local PM relative to AM is interpreted as indicating that most of these meteorites had perihelia of ~ 1 AU.

In this study we use the natural thermoluminescence of individual meteorites to estimate their closest approach to the Sun. Natural thermoluminescence is energy stored in crystals of certain minerals by ionizing radiation, such as high-energy galactic cosmic rays (Aitken 1985, McKeever 1985). This energy can be released in the form of visible light by heating.

The natural thermoluminescence (TL) of meteorites reflects both their thermal and irradiation history (McKeever 1980, Benoit *et al.* 1991). Virtually all ordinary chondrites have been exposed to galactic cosmic radiation for millions of years (Crabb and Schultz 1981), far longer than the $\sim 10^5$ years required to obtain TL equilibrium (Benoit *et al.* 1991). Depth effects on TL levels are minimal. TL profiles generally exhibiting $<30\%$ variation in even the largest meteorites (Benoit and Chen 1996). The intense

INTRODUCTION

Most meteorites are thought to be samples of asteroids (Wetherill 1985); however, it is unlikely that meteorites are random representative samples of their parent bodies. Their passage to Earth depends on their original orbit and the stochastic nature of the collisional events that ejected them into space (Wetherill 1985, Greenberg and Nolan 1989, Binzel *et al.* 1993). It has been proposed that some fraction of the meteorite flux derives from coherent orbital "streams" of meteoroids (Halliday 1987, Dodd *et al.* 1993). This idea is indirectly supported by orbital clustering of meteor-producing bodies and temporal clusters of meteoroid impacts on the Moon (Olsson-Steel 1988, Halliday *et al.* 1990, Drummond 1991, Oberst and Nakamura 1991). There is, however, little evidence that most meteorites were members of meteoroid streams at the time of their fall (Wetherill 1985).

heating of atmospheric passage drains natural TL in the outermost few millimeters of meteorites (Sears 1975, Benoit and Chen 1996), but we have deliberately avoided sampling these regions in this study. Therefore, the natural TL of modern falls is controlled largely by the maximum temperature experienced in space, which occurs at perihelion. The only exceptions are very large meteoroid bodies and meteoroids that have experienced shock heating within the last 10³ years, and both these exceptions appear to be very rare among the ordinary chondrites.

Following the treatment of Garlick and Gibson (1948), natural TL can be considered as the filling of "traps" by electrons put into the conduction band as a result of interaction with energetic particles, such as high-energy cosmic rays. The exact nature of these "traps" is presently unknown, but is generally considered to involve crystallographic defects and impurities (Prescott and Fox 1993). In crystals, populations of these "traps" are the source of TL, the electrons being freed from the traps and emitting a photon of light as the sample is heated. A typical TL experiment resulting in a "glow curve" involves heating a sample up to about 500°C in an inert atmosphere at a constant rate, while monitoring the amount of light given off by the sample as a function of temperature. In the present study we rearrange the basic equilibrium TL equation to solve for temperature (McKeever 1980, Benoit *et al.* 1991).

$$T = \frac{-E}{k \ln \left[\frac{([N/n] - 1) \ln(2)r}{sR} \right]}, \quad (1)$$

where n/N is the measured TL level relative to saturation. R is the radiation dose required to fill half the TL "traps," k is Boltzmann's constant, and r is the radiation dose rate. We use a dose rate of 0.01 Gy/year (1 rad/year) in our calculations; the actual dose rate experienced by samples will depend on the depths of the samples in the meteoroid, a factor we discuss below. E and s are characteristic of the TL phosphors, sodic feldspar in the case of ordinary chondrites, at a particular portion of the glow curve and they are essentially constants for ordinary chondrites (McKeever 1980). We can then calculate the distance from the Sun (X) from the calculated temperature assuming blackbody behavior.

$$X = \left[\frac{0.25\alpha H}{\varepsilon\sigma T^4} \right]^{1/2}. \quad (2)$$

where α and ε are the absorptivity and emissivity of the surface of the meteoroid body, H is the solar constant, and σ is the Stefan-Boltzmann constant (Melcher 1981). Using

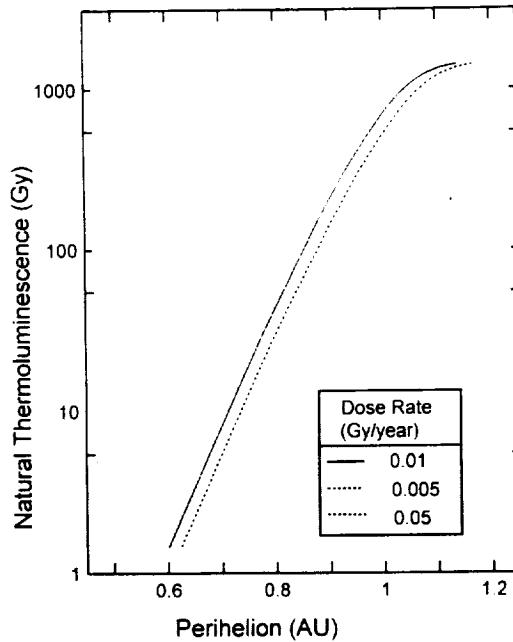


FIG. 1. Equilibrium natural thermoluminescence of ordinary chondrites at 250°C in the glow curve as a function of closest approach to the Sun (perihelion). Perihelion is given in astronomic units (AU).

a blackbody approximation in this case is appropriate because no asteroids, including those observed closely by space probes (Helfenstein *et al.* 1994), have atmospheres and the abundances of radioactive elements are too low in ordinary chondrites for these bodies to have any significant degree of internal heating during the last few million years. As a simplifying assumption, we set ε to unity and estimate a value of α of 0.85 from the albedos of meteorite samples in the laboratory and remote-sensing measurements of asteroid surfaces (Chapman and Salisbury 1973, Helfenstein *et al.* 1994). In Fig. 1 we show the relationship between natural TL level and perihelia for ordinary chondrites derived from Eqs. (1) and (2). This calculation shows that equilibrium natural TL levels exhibit a strong dependence on perihelia for perihelia < 1.1 AU. We show curves for three dose rates, ranging from 0.005 to 0.05 Gy/year. In the following discussion we quote perihelion values using the 0.01-Gy/year curve, an apparently typical value for ordinary chondrite meteoroid bodies (Benoit and Chen 1996, and references therein). The 0.005- and 0.05-Gy/year curves are more appropriate for samples from very small and very large meteoroid bodies, respectively, and it is apparent that differences in meteoroid size have fairly minimal effect on our interpretation.

When we give a perihelion value for a particular meteorite, numerous uncertainties are included, some of which cannot be estimated with accuracy. Equation (2) is suscep-

tible to uncertainties in albedo. Meteorite samples do exhibit some range of albedoes (Chapman and Salisbury 1973) and the relationship between the albedoes of meteorites and those of the surface of meteoroid bodies, of prime importance in this study, is not known. The major TL parameters, E and s , appear to exhibit little or no significant variation among ordinary chondrites (e.g., McKeever 1980), but, as mentioned above, some uncertainty is imposed because the size of the meteoroid body before atmospheric passage and the position of the TL sample in the body are generally not known, resulting in some uncertainty in dose rate. Because these uncertainties cannot be quantified, we base most of our analysis on our original TL data. The quotation of perihelion value, either below or in our figures, should be regarded as an interpretation of these data.

EXPERIMENTAL

For each meteorite we crushed an approximately 250-mg chip to a fine powder and removed metal (which is nonluminescent) with a hand magnet. We placed 4-mg aliquots of powder in copper pans which were then heated in a nitrogen atmosphere at a rate of 7.5°C/sec from room temperature to 500°C in a Daybreak Nuclear and Medical Systems TL apparatus fitted with blue bandpass and IR filters (Corning 7-59 and 4-69). Three aliquots of each sample were analyzed and the results averaged. Induced TL was measured by the same procedure 5 min after exposure to a 20-Gy dose from a ^{90}Sr - ^{90}Y source. We used the ratio of the low-temperature (250°C in the glow curve) peak to the high-temperature (400°C) peak to find the equivalent dose at 250°C in the glow curve, using a previously determined laboratory conversion equation (Hasan *et al.* 1987). The equivalent dose is the amount of radiation exposure needed to duplicate the observed natural TL level at a given temperature in the TL glow curve. A sample of a laboratory standard (the Dhajala H3.8 meteorite) was analyzed at the start and end of each measurement period as both a normalization standard and a check on the long-term stability of the apparatus.

Uncertainties in the natural TL data from analytical sources, as determined by triplicate measurements on each sample, are quite small, being generally a few percent of the natural TL level, except for TL levels below about 15 Gy that may have analytical uncertainties of up to 10–15%. We did not collect multiple samples from each meteorite and therefore we cannot directly assess the uncertainties caused by depth dependence; however, detailed TL studies of other meteorites indicate that typical sample-to-sample heterogeneity in meteorites introduces uncertainties of no more than 10% (Benoit and Chen 1996). With the exception of meteorites with very low natural TL levels (<15

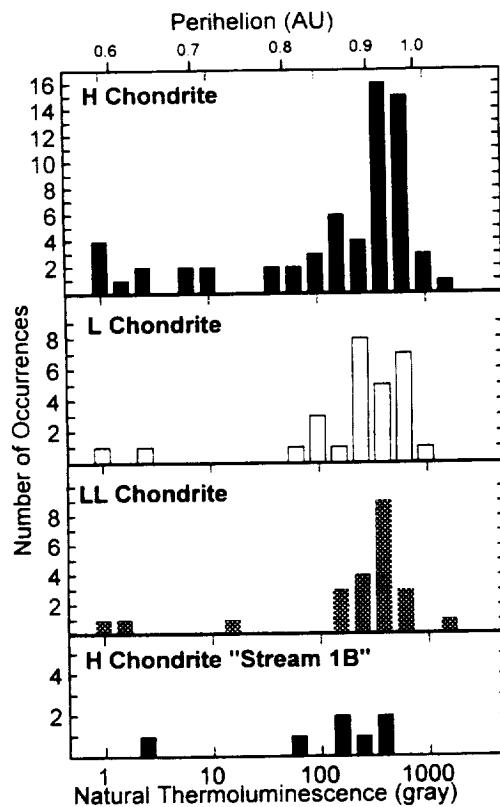


FIG. 2. Natural thermoluminescence at 250°C in the glow curve for ordinary chondrites. The distributions for H, L, and LL chondrites are fairly similar and correspond to orbits with perihelia between ~ 0.75 and ~ 1.0 AU. Members of a possible H chondrite orbital debris stream (Dodd *et al.* 1993) have a distribution similar to that of other ordinary chondrites.

Gy), uncertainties in our data are no larger than the size of width of the boxes on our histograms (Fig. 2).

RESULTS

We have determined natural TL levels for 118 equilibrated ordinary chondrites (Fig. 2). Our previous work indicates that the natural TL levels of equilibrated ordinary chondrites are not affected by nonthermal losses or anomalous fading (Wintle 1973, Sears *et al.* 1991). There are no significant differences in natural TL between the major classes, the H, L, and LL chondrites, all classes having natural TL values of 50 to 1000 Gy, with a few outliers at lower values.

DISCUSSION

We can convert the natural TL data for individual meteorites to perihelion using Eqs. (1) and (2). As noted above, such a conversion carries uncertainties that cannot be quantified, but differences of a few hundredths of an AU

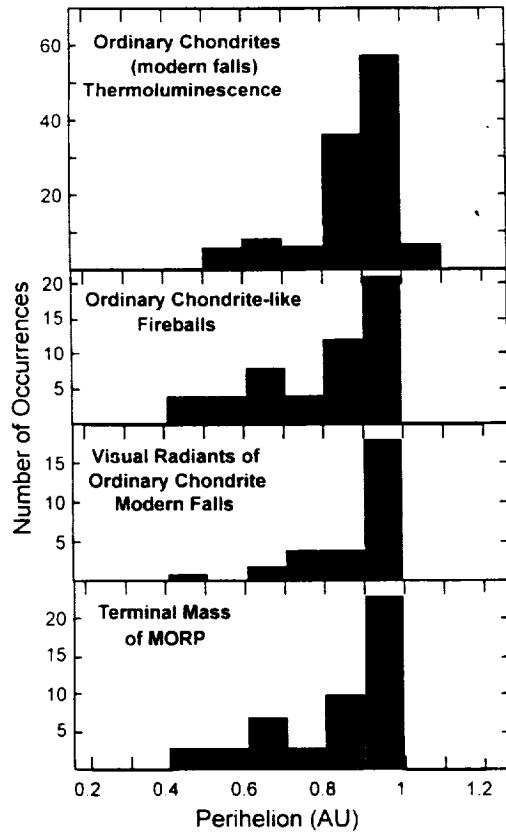


FIG. 3. An interpretation of the natural TL data for ordinary chondrites (Fig. 2), using Eqs. (1) and (2) to convert the TL data to perihelia. For comparison, perihelion distributions derived from chondrite-like fireballs (Wetherill and ReVelle 1981), visual radiants of observed meteorite falls (Simonenko 1975), and MROP fireballs (Halliday *et al.* 1983) are also shown. In general, the distribution derived from TL is similar to other distributions, and is most similar to those exhibited by chondrite-like fireballs and the distribution derived from MROP fireballs.

are probably significant in comparisons between meteorites. The range of natural TL levels corresponds to perihelia of 0.75 to 1.0 AU, with an average around 0.95 AU, with just a few outliers with perihelia <0.75 and >1.0 AU (Fig. 2). This distribution is in general agreement with the distribution suggested by observed meteorite falls and also with the more numerous meteor and fireball radiant data (Fig. 3) (Wetherill and Chapman 1988). The distribution derived from the natural TL of meteorites is most similar to the distribution observed for fireballs attributed to ordinary chondrite objects, defined by two different methods (Wetherill and ReVelle 1981, Halliday *et al.* 1983), and differs from the distribution derived from visual radiants of ordinary chondrite falls by having a larger proportion of meteorites with perihelia between 0.8 and 0.9 AU. The most likely cause of this difference, as discussed by Wetherill and ReVelle (1981), is biases inherent in the estimates of orbits from radiants observed by untrained persons.

The outliers with natural TL levels <50 Gy (Fig. 2) are not discussed further here and are not considered in our statistics, because it is possible that some of these meteorites had their TL levels lowered by recent shock heating or we may have accidentally sampled material near the fusion crust created during atmospheric passage. Thus, for these meteorites, the natural TL level could reflect a heating event other than closest approach to the Sun.

As was noted above, one of the key observations that led to the delineation of the orbits and source of meteorites was the AM/PM time-of-fall distribution (Wetherill 1968). We would expect such differences also to be reflected in the TL data and we do find such differences in at least two of the major ordinary chondrite classes (Fig. 4). The H chondrites that fell in the local AM have a mean natural TL level similar to that of chondrites that fell in the PM

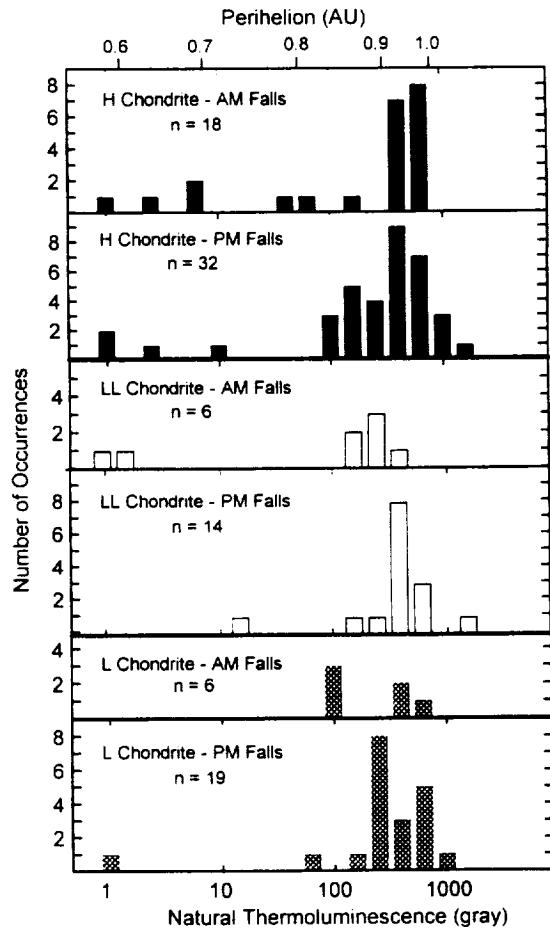


FIG. 4. Natural thermoluminescence distributions for H, L, and LL chondrites that fell in the AM and PM local time. For H chondrites the AM falls exhibit a lower degree of variation than PM falls, whereas for LL chondrites the AM falls generally have lower TL levels than PM falls. Only meteorites with natural TL levels >50 Gy are considered in our statistics and the total number used for each class and time-of-fall is given by n .

(about 300 Gy), but the AM falls had a much smaller standard deviation, lacking the large number of samples with natural TL of 100–300 Gy present in the PM falls (Fig. 2). The *F* test, used to examine equality of variance between data sets (Davis 1986), indicates that this difference is significant at the 95% confidence level and is thus probably not simply due to the smaller number of AM falls in our study. The LL chondrites that fell in the local AM have lower natural TL levels than PM falls, the difference being significant at the 99% confidence level according to the *t* test, but the distributions have similar variances. There are no significant differences in the TL distributions of L chondrite AM and PM falls.

Our interpretation of these data is that the AM falls of LL chondrites have perihelia between 0.85 and 0.90 AU, whereas the PM falls are dominated by meteorites with perihelia between 0.85 and 1.0 AU. On the basis of the orbital dynamics arguments of Wetherill (1968), it can be argued that these data support the conclusion that LL chondrites are a steady-state population derived from the asteroid belt via orbital resonances that preferentially place them in orbits with perihelia of ~1 AU. These bodies are short-lived, being removed from the inner solar system by interactions with planets on the 10⁶-year time scale, and only a few objects achieve orbits with perihelia significantly <1 AU. Our data indicate that very few LL chondrites that reach Earth have perihelia <0.8 AU. An alternative interpretation of these data is that the AM and PM fall samples experienced different dose rates as a result of AM falls being larger than PM falls. Our investigations of TL profiles in meteorites, however, suggest that the observed difference would require all AM falls to be larger than typical meteoroid bodies (Benoit and Chen 1996). Such a conclusion is not supported by the size-dependent ratios of cosmogenic noble gases in LL chondrites (Graf and Marti 1994).

The H chondrites have a more complicated apparent orbital distribution (Fig. 4). While the AM falls have perihelia values of ~0.95 AU, the PM falls, which should be dominated by meteorites with perihelia of about 1 AU, exhibit a range of 0.80 to 1.0 AU with a significant number <0.9 AU. One possible interpretation of this result is that the PM falls exhibit an extreme range of preatmospheric sizes and the AM falls are very homogeneous in size. This interpretation is not supported by the ratios of cosmogenic noble gases found in these meteorites such as ²¹Ne and ²²Ne, which vary as a function of meteoroid size (Eugster 1988, Michel *et al.* 1991).

An alternative interpretation of these data is that the H chondrites with TL levels between 100 and 300 Gy in the PM falls experienced shock heating within the last 10⁵ years, the time required for TL to rebuild to thermally controlled equilibrium; however, these meteorites display no petrographic evidence for high levels of shock. Another possibil-

TABLE I
H Chondrites in an Inferred Orbital Cluster

Meteorite	Class	Cosmic ray exposure age (Ma)	²² Ne/ ²¹ Ne
Barbotan	H5	9	1.10
Beaver Creek	H4	29	1.04
Charsonville	H6	55	1.06
Forest City	H5	6	1.08
Gopalpur	H5	10	1.24
Lillaverke	H5	—	—
Noblesville	H4	—	—
Pokhra	H5	3	1.24
Pribram	H5	15	1.11
Rochester	H6	25	1.07
St. Germain du Pinel	H6	36	1.14
Zhovtnevy	H5	42	1.08

ity is that these meteorites were in orbits with perihelia of about 0.8 AU but moved to orbits with perihelia of ~1 AU within the last 10⁵ years. Such rapid orbit changes are possible, or even expected, for Earth-crossing asteroids as a result of orbital interactions with planets (Galibina and Terent'eva 1987, Farinella *et al.* 1993). We have previously described a large Antarctic meteorite shower that apparently underwent rapid evolution from orbits with perihelia >1.2 AU to ~1 AU (Benoit and Sears 1993b). This interpretation, however, requires that these meteorites changed orbit as a group. This could occur if these meteorites were part a single body that fragmented after changing orbit, but this seems unlikely due to their petrographic diversity (encompassing petrographic types 4, 5, and 6) and wide range of cosmic ray exposure ages (Table I). Alternatively, they could have formed an orbital debris "stream," similar to those that produce meteor showers (Olsson-Steel 1988, Halliday *et al.* 1990). In this case, these meteorites reach Earth only when Earth's orbit intersects the stream.

Dodd *et al.* (1993) have examined the time-of-fall statistics for H chondrites in an attempt to identify possible orbital streams among historical falls. They proposed that a small subset of H chondrites (including some of the PM falls with apparent perihelia of ~0.8 AU in our data set) were in an orbital stream, called H Cluster 1. Our analysis of 7 of 11 potential members of this stream, however, indicates that there is no difference between their TL distribution and that of other H chondrites (Fig. 2), suggesting that these meteorites did not have similar perihelia in their recent history and thus were probably not members of a modern orbital stream. This conclusion, however, rests on the assumption that a meteoroid stream has a stable orbit on the time scale reflected in the collection of modern falls, namely, on the scale of a few decades up to about a century, and thus that such streams are similar to the debris streams

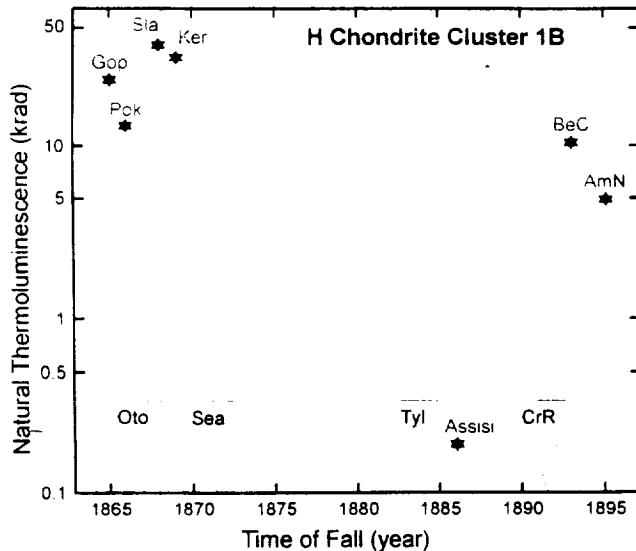


FIG. 5. Natural thermoluminescence levels of H chondrites from the proposed Cluster 1B orbital stream of Dodd *et al.* (1993), plotted as a function of their year of fall. Meteorites in triangles along the bottom axis were not analyzed in this study. Meteorites that fell before about the year 1870 exhibit a fairly tight range of natural TL levels, consistent with perihelia slightly less than 0.95 AU. Those that fell after the year 1885 have lower natural TL levels, possibly reflecting perihelia less than about 0.85 AU. AmN, Ambapur Nagla; BeC, Beaver Creek; CrR, Cross Roads; Gop, Gopalpur; Ker, Kernoué; Oto, Otomi; Pok, Pokra; Sea, Searsmont; Sla, Slavetic; Tyl, Tynes Island.

responsible for meteor showers. Dodd *et al.* (1993) point out that a subset of the proposed H Chondrite Cluster 1, the 1B stream, is not so well behaved and, although the members of the proposed stream fell over a period of about 30 years (1865–1895), there is a pronounced gap within this range of about 12 years (1872–1883) in which no potential members fell. They suggest this reflects the narrow width of the stream and perhaps an orbit inclined to the ecliptic. We note that there is an apparent difference in the TL levels of meteorites from the proposed stream depending on their year of fall (Fig. 5). Meteorites that fell before the gap appear to have moderate natural TL levels, consistent with perihelia of slightly less than 0.95 AU. Meteorites that fell after the gap, however, have significantly lower natural TL levels, consistent with perihelia of <0.85 AU, and one, Assisi, may have had a perihelion of about 0.6 AU (Benoit *et al.* 1991). It is unlikely that Assisi experienced TL loss due to a recent shock event, having a low petrographic shock level (Dodd *et al.* 1993) and a TL sensitivity of 4.3 ± 0.2 relative to the Dhajala meteorite, similar to other unshocked equilibrated ordinary chondrites (Haq *et al.* 1988). The apparent gap in the proposed Cluster 1B could reflect a change in the orbit of the stream, with the members of the stream achieving much lower perihelia after the gap, or, conversely, this could reflect the sampling

of different portions of a narrow stream by slight variations in the Earth's orbit. From the perspective of Fig. 4, in contradiction of the summary data of Fig. 2, it appears more likely that the proposed Cluster 1B is actually a meteoroid stream, albeit a rapidly evolving one, with the stream breaking up in the second encounter. We stress, however, that this conclusion is of necessity based on a very small number of meteorites.

CONCLUSIONS

Only a small fraction (<25%) of the H chondrites we have analyzed are involved in an inferred orbital cluster. In general, our data indicate that the remainder fit into the model of meteoroid orbital distribution suggested by Wetherill (1968). Most ordinary chondrites appear to have been in orbits with perihelia between 0.8 and 1.0 AU prior to reaching Earth, and therefore they were probably derived as individuals from the asteroid belt through orbital resonance with the major planets. We find differences between the orbital distributions of meteorites falling in the local morning and those falling in the afternoon and evening. As predicted from indirect data, most ordinary chondrites were in orbits with perihelia >0.85 AU, but we suggest that a small fraction of meteorites have experienced recent histories involving rapid orbital changes. We find some support for the existence of a rapidly evolving stream of H chondrites, previously suggested on the basis of time-of-fall data. In general, it can be argued that minor, but perhaps important, changes have occurred in the numbers and types of meteorites reaching Earth on the $<10^5$ -year time scale.

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